Soft and Hard probes of proton multiple scattering in \( p+Pb \) collisions with the ATLAS experiment at the LHC

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Motivation

The study of particle production and scaling properties and underlying nature of p+Pb collisions,

In p+Pb, nucleons are struck multiple times. Simply an incoherent sum of nucleon-nucleon interactions?

- Hard Probes: Inclusive Jets and Z bosons
- Soft Probes: Charged particle $\eta$ distributions.

Allow the study initial state nuclear effects.

https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults
p+Pb data Data: 2012 (1$\mu b^{-1}$) and 2013 (30 $nb^{-1}$). 
$p = 4$ TeV, Pb = 1.57 TeV/A, $\sqrt{s_{NN}} = 5.02$ TeV and $\Delta y \approx \pm 0.47$.

Results presented are based on measurements of:

1. Electrons (ID, MS, CAL)
2. Muons (ID, MS)
3. Charged particles (ID)
4. Jets (ID, CAL)
5. Event activity (FCAL)
6. + trigger system
Experimental Selection of Centrality

Geometry of the p+Pb collision is indirectly constrained by measurements of soft particle production in Pb going direction. (sensitive to multiple interactions in Pb nucleus).

- Centrality characterized by the total $E_T$ deposited in Pb-going Forward Calorimeters.
- Centrality classes defined with percentiles of total $E_T$: 0-1% (most central), 5-10%, 10-20%...60-90% (most peripheral).
- Class 90-100% excluded from analysis.
Centrality and Geometry

Estimate the number of nucleons that participate in the p+Pb collision, $N_{part}$, for each centrality class.

- Geometry estimated with semi-classical model. “Glauber” with $\sigma_{NN} = 70 \pm 5$ mb, and
- “Glauber-Gribov” extension with event-by-event fluctuations on $\sigma_{NN}$ controlled by $\Omega$, estimated from data PLB 633 (2006), PLB 722 (2013).
- Monte Carlo simulation and fit to measured FCAL $E_T$ used to estimate $\langle N_{part} \rangle$ in each centrality class.
Charged particle reconstruction

- Hits in the first three Pixel detector layers are used.
- Three methods with different systematics and acceptance.
  - Two 2-point tracklet methods. (black and red).
  - 3-point track method (extrapolated to $p_T=0$). (blue)
- Consistency among methods after corrections. ✓
Charged particle multiplicity vs centrality

$dN_{\text{ch}}/d\eta$ measured for $|\eta| < 2.7$ in eight centrality intervals.

- Visible double peak structure.
- Distribution asymmetry has strong centrality dependence.

\( \eta < 0 \) is proton-going.
Ratios to the most peripheral distribution

$\eta < 0$ is proton-going.

- Divide by the most peripheral (60-90%) events “$pp$ like”.
- Double peak divides out
- Ratio grows linearly with $\eta$. Centrality dependent slope
\(N_{\text{part}} \) scaling

- Normalized to \( \langle N_{\text{part}}/2 \rangle \) for 0-1% and 60-90% events.
- Same data but different \( \langle N_{\text{part}} \rangle \) according to three geometrical models.
- Intercept (scaling) occurs at different \( \eta \) for the different models.
- Central events show enhancement at Pb-going side, or suppression at \( p \)-going side depending on model.

\[ \eta < 0 \text{ is proton-going.} \]
Z boson reconstruction: $Z \rightarrow \mu\mu$ and $Z \rightarrow ee$

- Dimuon and dielectron channel used. Good agreement; results are combined.
- MC: Powheg CT10, PYTHIA8 showering. Used to correct data. Checked with data-driven methods.
- MC is normalized to total NNLO prediction, used as baseline.
Z boson differential cross-sections

\[ \sigma_{p+Pb, Z} \frac{dN}{dy} \]

\[ 1/2 \text{ for } y^Z \geq 0 \text{ is proton-going.} \]

- Significant excess at Pb going side with respect to CT10.
Z boson: $N_{coll}$-scaled centrality differential yield

$y > 0$ is proton-going.

- Significant excess at Pb going side only seen at central events. (Standard Glauber...)

ATLAS Preliminary  
$p+\text{Pb} 2013, L_{int} = 29 \text{ nb}^{-1} \sqrt{s_{NN}} = 5.02 \text{ TeV}$

$\langle N_{coll}^{-1} \frac{dN_{p+\text{Pb} \rightarrow Z^{0} \rightarrow \nu\bar{\nu}}}{dy} \rangle_{\Omega=0}$

Glauber ($\Omega=0$)
- 0-10% Centrality, $\langle y^{Z} \rangle = 0.23 \pm 0.08$
- 10-40% Centrality, $\langle y^{Z} \rangle = 0.16 \pm 0.06$
- 40-90% Centrality, $\langle y^{Z} \rangle = 0.58 \pm 0.16$

CT10 Model
$y > 0$ is proton-going.

- Same data but different $N_{\text{coll}}$ according to three geometric models
- Central events show enhancement at Pb going side, or suppression at $p$ going side depending on geometric model.
- Similar trend as in charged particle multiplicity
Ratio: $Z$ bosons / charged particle multiplicity

**Expectation**

$Z$ bosons $\propto$ number of binary nucleon-nucleon collisions. $\langle N_{\text{coll}} \rangle$

$dN_{\text{ch}}/\eta \propto$ number of participants nucleons $\langle N_{\text{par}} \rangle$

- In $p+Pb$ collisions
  $\langle N_{\text{coll}} \rangle = \langle N_{\text{par}} \rangle - 1$

- Ratio (model independent) is plotted three times. Glauber model and two extensions.

- Data consistent with expectations
Geometric scaling

Z bosons

Scaling behaviour quite sensitive to geometric modelling.
Similar trends in these two different observables.
Jets in $p+Pb$

- anti-kt $R=0.4$ calorimeter jets.
- Underlying Event estimated and subtracted with technique designed for Pb+Pb, checked with $pp$
- Measured in intervals of $y^* = y - \Delta y$, $p_T$ and centrality.
Central to Peripheral Ratio

Null Hypothesis

p+Pb collisions behave like an incoherent superposition of nucleon-nucleon collisions. That is, there is geometric scaling

Observable

\[ R_{CP} = \frac{(1/N_{evt})dN^2/dp_T dy^\ast}{(1/N_{evt})dN^2/dp_T dy^\ast} \times R_{coll} \]

- Per-event yield in Central p+Pb collisions.
- Per-event yield in Peripheral p+Pb collisions.
- Ratio of \( \langle N_{coll} \rangle \) at central and peripheral. Glauber model

In the absence of nuclear effects, \( R_{CP} \approx 1 \).
Jet $R_{CP}$

$y^* > 0$ is proton-going.

- Larger suppression at large $p_T$.
- Smooth centrality dependence.
- Suppression more pronounced at large $y^*$, present even at negative $y^*$.
**Nuclear modification factor**

**Null Hypothesis**

p+Pb collisions behave like an incoherent superposition of nucleon-nucleon collisions. That is, there is geometric scaling.

**Observable**

\[
R_{pPb} = \frac{(1/N_{evt}) dN^2 / dp_T dy^*}{T_{pA} \times d\sigma^2 / dp_T dy^*}
\]

- Per-event yield in p+Pb collisions at \( \sqrt{s} = 5.02 \) TeV
- Cross-section in pp collisions at \( \sqrt{s} = 2.76 \) TeV \( x_T \)-scaled to \( \sqrt{s} = 5.02 \) TeV.
- Nuclear thickness function \( \propto \langle N_{coll} \rangle \), from Glauber Model.

In absence of nuclear effects

\[
R_{pPb} = 1
\]
Jet $R_{pPb}$ integrated in centrality.

$y^* > 0$ is proton-going.

- Includes events in 0-90% centrality.
- $\approx 5\text{--}10\%$ enhancement over geometric scaling.
- Consistent with predictions, nPDF EPS09.
Jet $R_{pPb}$ vs centrality.

$y^* > 0$ is proton-going.

0-10% centrality.
Suppressed.

60-90% centrality
Enhanced!

- Larger modifications at large $p_T$ and forward $y^*$
- Geometric scaling at low $p_T$ and backward $y^*$
If the data is presented vs \( p = p_T \cosh(y^*) \) (total jet energy)

\[ \int L dt = 27.8 \text{ nb}^{-1} \]

\( p+\text{Pb} \quad s_{NN} = 5.02 \text{ TeV} \)

anti-\( k_t \), \( R=0.4 \)

\( y^* > 0 \) is proton-going.

- Data at forward \( y^* \) follow same trend.
- Implications for underlying suppression mechanism?
\( R_{pPb} \) vs \( p \) in central and peripheral events.

If the data is presented vs \( p = p_T \cosh(y^*) \) (total jet energy)

- Jet energy scaling less perfect, but present in both central and peripheral events.
Conclusions

- $dN/d\eta$ shows strong centrality dependent asymmetry.
  - Almost linear $\eta$ dependence when scaled by peripheral (proxy to pp).
- $Z$ rapidity cross-sections show significant asymmetry.
  - Centrality dependent.
- Scaled $Z$ bosons and $dN/d\eta$ show similar $N_{part}$ dependence.
  - Behaviour dependent on geometric model.
  - Show the importance of considering fluctuations in $\sigma_{NN}$
- Jet rates mildly enhanced in 0-90% centrality.
  - Consistent with nPDFs expectations
- Strong centrality dependence effects in jets yields.
  - At high $p_T$, suppression for central events and enhancement for peripheral events.

Stay tuned for more p+Pb results: https://twiki.cern.ch/twiki/bin/view/AtlasPublic/HeavyIonsPublicResults
**ATLAS** Preliminary
PYTHIA 8, 5.02 TeV

fit to gamma function
$k_0 = 1.402, \theta_0 = 3.414$

**ATLAS** Preliminary
$p+\text{Pb} \mid s_{NN} = 5.02 \text{ TeV}$
- standard Glauber
- Glauber-Gribov $\Omega=0.55$
- Glauber-Gribov $\Omega=1.01$
**ATLAS** Simulation Preliminary

\( p+Pb, \sqrt{s_{NN}} = 5.02\ \text{TeV} \)

\( L_{\text{int}} = 1\ \mu\text{b}^{-1} \)

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\[ \langle N_{\text{part}} \rangle \]

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\[ \frac{1}{N_{\text{evt}}} \frac{dN}{d\Sigma E_T^{Pb}} \] [GeV^{-1}]

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ATLAS Preliminary

\( p+Pb, L_{\text{int}} = 1\ \mu\text{b}^{-1} \)

\( \sqrt{s_{NN}} = 5.02\ \text{TeV} \)

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- **Glauber**
- **Glauber-Gribov, \( \Omega = 0.55 \)**
- **Glauber-Gribov, \( \Omega = 1.01 \)**

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**fit / data**

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\( \Sigma E_T^{Pb} \) [GeV]

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ATLAS Preliminary

$p+Pb \sqrt{s_{NN}} = 5.02$ TeV

$P_H(\sigma_{NN})$

- Blue line: Glauber-Gribov $\Omega=0.55$
- Red line: Glauber-Gribov $\Omega=1.01$

$\sigma_{NN}$ [mb]